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STRESSES AROUND CENTRAL HOLES IN A STIFFENED ORTHOTROPIC STRIP

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Stresses around central holes in a stiffened orthotropic strip

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ABSTRACT

This paper deals with the stress analysis of orthotropic panels with edge stiffeners and central holes, elliptical or circular in cross section. Stress profiles are obtained for fixed hole geometry as functions of stiffener geometry. Stress variations are also computed as functions of hole size for different stiffening geometries.

1. Introduction

This paper forms part of an experimental and theoretical study, undertaken at the Army Materials and Mechanics Research Center to examine the role of stiffener geometry and material properties on the stresses around discontinuities such as holes or cracks in panels of fibrous composites. The analysis assumes a homogeneous orthotropic model as a first approximation to the actual fiber composite behaviour. The effects of stiffener geometry and material orthotropy on the stress-intensity factors of centrally placed cracks in a stiffened panel as well as those in wide panels with multiple stringers were reported in [1] and [2]. Important as these results are from a fracture mechanics standpoint, the adequacy of the assumed orthotropic behaviour is more readily verified experimentally by concentrating on stress distributions without singularities such as crack-tips. This paper provides the results for centrally placed stress free holes, circular or elliptical, in a stiffened panel under tension at the free ends.

The analysis of this paper is based on Isida's method [3], originally developed for isotropic problems of stresses around discontinuities in strips, after modifications to suit the present orthotropic problem. For details of analysis, particularly for the hole problem [4] may be seen.

2. Analytical formulation

2.1. *Boundary value problem*

Figure 1a depicts the geometry and the loading of the problem considered. The half-width of the strip is taken as the unit of length and all lengths (including coordinate distances) are normalized with respect to it. The strip is assumed to be infinitely long and under uniform tensile stress T at the far ends. The central elliptical (or circular) hole is stress free.

The boundary conditions at the stiffeners are based on the assumption that they are beam-like elements with a single characteristic material constant, E_s the modulus.

From the free-body diagrams of Figs. 1b and 1c we find the boundary conditions to be:

$$\begin{aligned} [\sigma_{xy}]_{y=1} &= \hat{a}(E_s/E_x)[\sigma_{xs,x}]_{y=1} \\ [\sigma_y]_{y=1} &= \hat{b}(E_s/E_x)[v_{,xxxx}]_{y=1} \end{aligned} \tag{1}$$

where $\hat{a}$ and $\hat{b}$ are, respectively, the dimensionless relative shear and bending stiffnesses of the stiffener. Although $\hat{a}$ and $\hat{b}$ are related quantities for a given geometry of stiffener, it is convenient to treat them as independent parameters and characterize the stiffener influence through them. Thus $\hat{a}=\hat{b}=0$ gives the familiar unstiffened (free) strip problem, while $\hat{a}=\hat{b}\rightarrow\infty$ corresponds to the case of a strip with the straight edges clamped [3]. In Eqn. (1) σ_{xs} denotes the σ_x value in the stiffener.

2.2. *Stress function*

The plane orthotropic crack problem considered here falls in class of elastostatic problems of

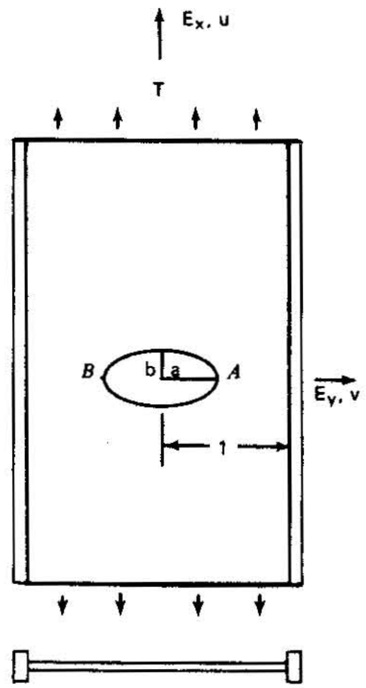

Figure 1a. Boundary value problem.

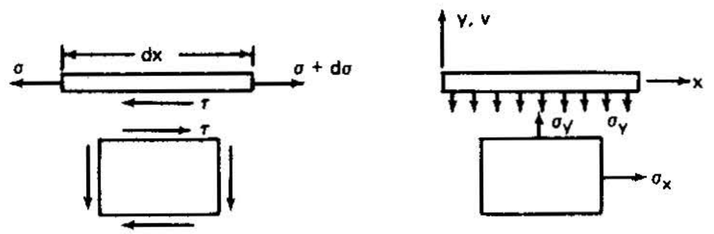

Figure 1b. Free body diagram for determining the boundary conditions at the straight edges.

generalized plane stress as treated by Lekhnitskii [5]. The solution lies in obtaining a stress function as an analytical function of a complex variable from which all the stresses and displacements throughout the region of interest are derivable and which satisfies the given boundary conditions. The usual procedure consists of assuming the stress function to be a Laurent-type power series in Z, the complex variable, so that each term satisfies the given plane biharmonic equation and whose coefficients can be adjusted to satisfy the boundary conditions as well as numerically possible. The orthotropic problem is characterized by the existence, in addition to the complex variable Z, of two associated complex variables Z_1 and Z_2 as linear combinations of Z and its conjugate $\bar{Z}$. Thus:

$$2Z_\alpha = \gamma_\alpha Z + \delta_\alpha \bar{Z} \quad (\alpha = 1, 2) \tag{2}$$

where γ_α, δ_α are in general complex combinations of the elastic constants. However, in special cases of symmetry and for certain combinations of the elastic constants they take the simple form:

$$\gamma_\alpha = 1 + \beta_\alpha \ ; \quad \delta_\alpha = 1 - \beta_\alpha \qquad (\alpha = 1, 2) \tag{3}$$

where β_α are real positive dimensionless combinations of the elastic constants as shown in [4]. It is simple to show that the isotropic case corresponds to $\beta_1 = \beta_2 = 1$. Hence the stress function for the orthotropic case consists of a pair of analytical functions $F_\alpha(Z_\alpha)$.

For the particular boundary value problem considered, the stress function is conveniently taken as:

$$F_\alpha'(Z_\alpha) = T\left[\frac{\beta_\alpha^2}{2(\beta_\sigma^2-\beta_\alpha^2)} + \sum_{n=0}^{\infty}(2n+1)C_{2n,\alpha}Z_\alpha^{-(2n+2)} + \int_0^\infty K_{2n,\alpha}\cos mZ_\alpha \mathrm{d}m\right] \tag{4}$$

$\alpha, \sigma = 1, 2$; $\alpha \neq \sigma$

The goal is now to determine $C_{2n,\alpha}$ and $K_{2n,\alpha}$ from the boundary conditions at the stiffener and the stress free condition at the hole. Once these coefficients are determined we can obtain the stresses throughout the region of interest quite readily from the stress function. In particular, we can write the expression for the maximum stress at a concentration point (point A or B in Fig. 1a) for the elliptical (or the circular case) as a power series in the relative axial length of the hole, thus:

Ellipse:

$$\frac{\sigma_x}{T} = 1+(\beta_1+\beta_2)\frac{a}{b} + B_2a^2+B_4a^4+B_6a^6+\dots B_{2n}a^{2n}+\dots \tag{5}$$

Circle:

$$\frac{\sigma_x}{T} = 1+(\beta_1+\beta_2)+B_2'\lambda^2+B_4'\lambda^4+B_6'\lambda^6+\dots B_{2n}'\lambda^{2n}+\dots \tag{6}$$

where B_{2n} and B_{2n}' are functions of the orthotropic parameters β_1, β_2 and the stiffener factors $\hat{a}$, $\hat{b}$ of the stiffeners. B_{2n} also involve the geometry of the ellipse as powers of (a/b).

From Eqns. (5) and (6) it is seen that for $a \to 0$ $(b \to 0)$ or $\lambda \to 0$ we have the situation of a small hole in an infinite region; and in particular by setting $\beta_1 = \beta_2 = 1$ we obtain the well-known stress concentration formulae for the isotropic plane as

$$\begin{aligned} \sigma_x/T &= 1+2a/b \quad &\text{(ellipse)}\\ &= 3 &\text{(circle)}\end{aligned}$$

3. Discussion of results and concluding remarks

Equations (5) and (6) have been computed for different values of $\hat{a}$, $\hat{b}$ and a (keeping a/b fixed for the elliptic case) for given values of β_1 and β_2 characteristic of a fiber-glass laminate of 50 % volume fraction with the following properties:

$E_x = 5\times10^6$ psi $\quad E_y = 2.0\times10^6$ psi $\quad G_{xy} = 4\times10^5$ psi

$\nu_{yx} = 0.1 \quad\quad \nu_{xy} = 0.25$

yielding $\beta_1 = 3.4334 \quad \beta_2 = 0.4605$

The stiffener has been assumed to be of the same orthotropic material as the strip so that $E_s = E_x$ in Eqn. (1).

Before the results are discussed two points are worth mentioning: firstly, the present paper truncates Eqns. (5) or (6) to λ^{10}; there is no proper way of estimating the error in truncating the series. However, the coefficients B_{2n} in all the cases examined decrease in size so that a convergence in an asymptotic sense is possible. Secondly, Isida [3] has shown that λ should be $\leq 0.9 \sim 0.95$ for the validity of the present perturbation solution.

From Eqn. (1) it is seen that the limiting "clamped" case of $a = b \to \infty$ will yield the following boundary conditions at $y = 1$.

$$\sigma_{xs,x} = v_{,xxxx} = 0\,. \tag{7}$$

Hence, at the edge $y = 1$, $\sigma_{xs}]_{x=0} = \sigma_{xs}]_{x=\infty} = T$.

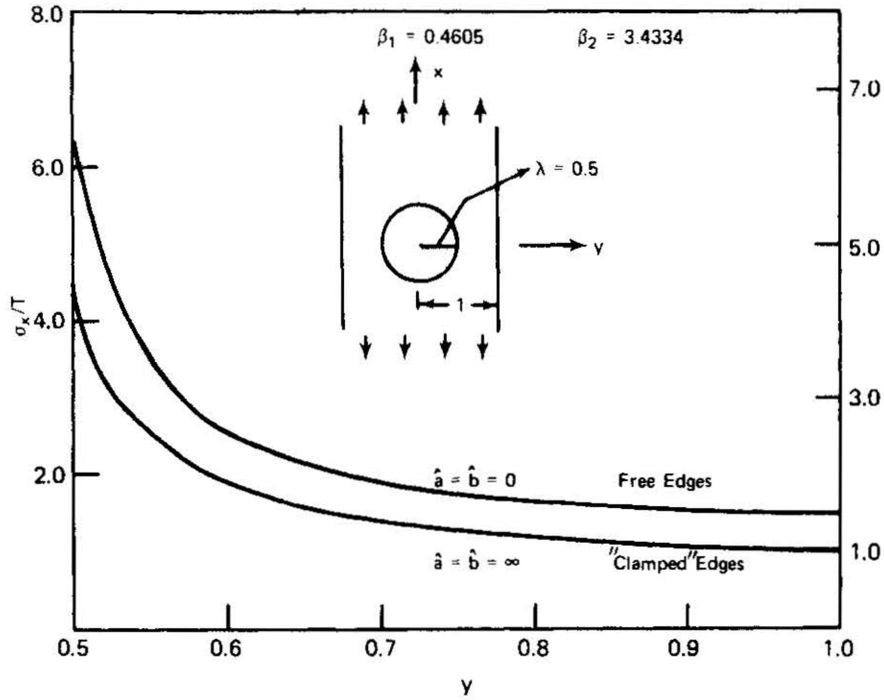

Figure 2a. Stress profile for a circular hole.

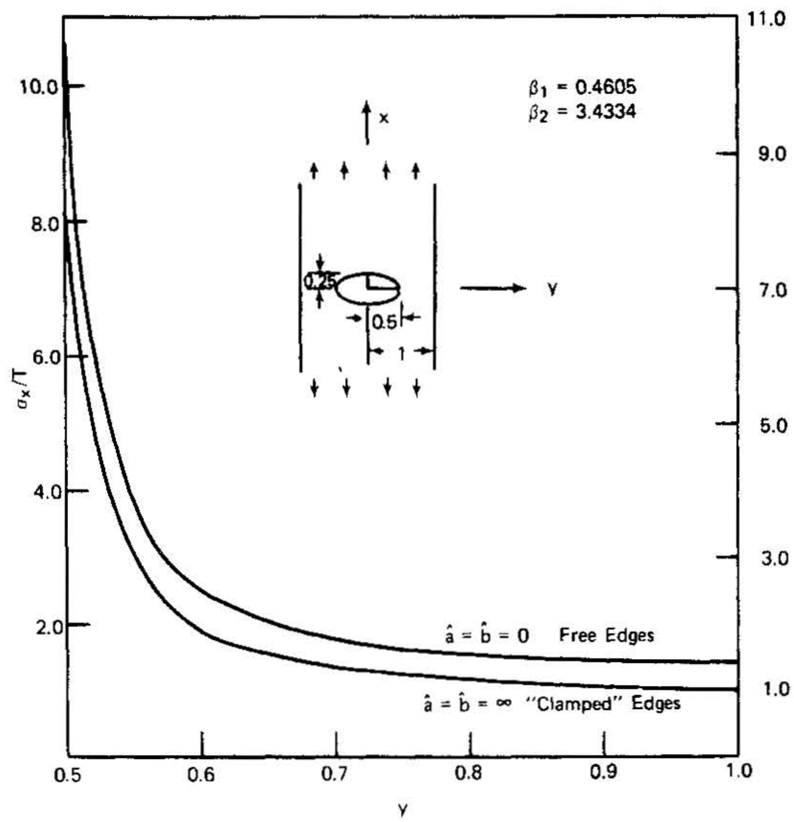

Figure 2b. Stress profile for an elliptical hole.

Thus, the maximum-stress profile for a typical hole with "clamped" edges will reach the value T at the edge.

In Figs. 2a and 2b the maximum-stress profiles are shown for the limiting values of a and b for a circular hole and an elliptical hole for the above choice of orthotropic parameters. The hole geometry is fixed with $a/b=2.0$ and $a=0.5$ for the elliptical case and $a=b=0.5$ for the circular case. The stress profiles conform to the ideas of stress concentration for the configurations. The elliptical case exhibits larger stress concentration than the circular case; also the "clamped" edge results in lower stress values.

In Figs. 3a and 3b, the variation of maximum-stress ratio is shown as a function of hole size for different values of the stiffening parameters $\hat{a}$ and $\hat{b}$. Defining $K=\sigma_x/T$ at the concentration

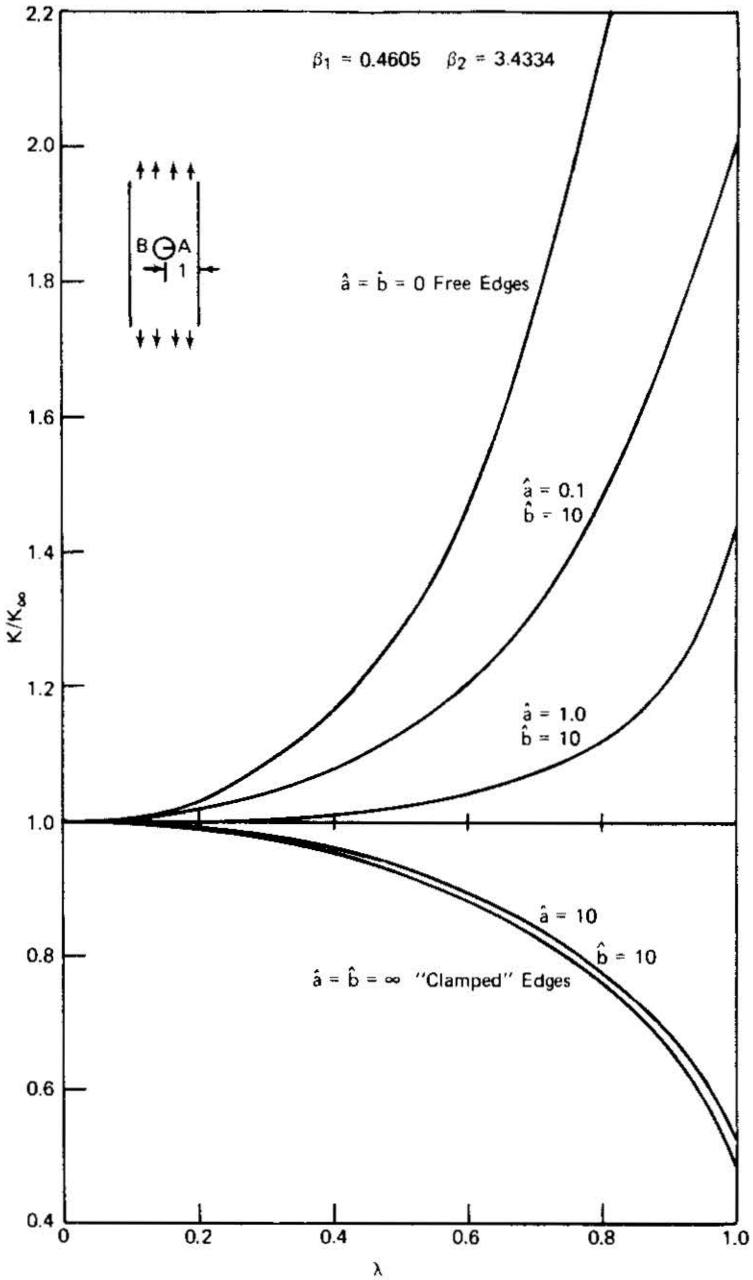

Figure 3a. Variation of peak stress with hole size: circular case.

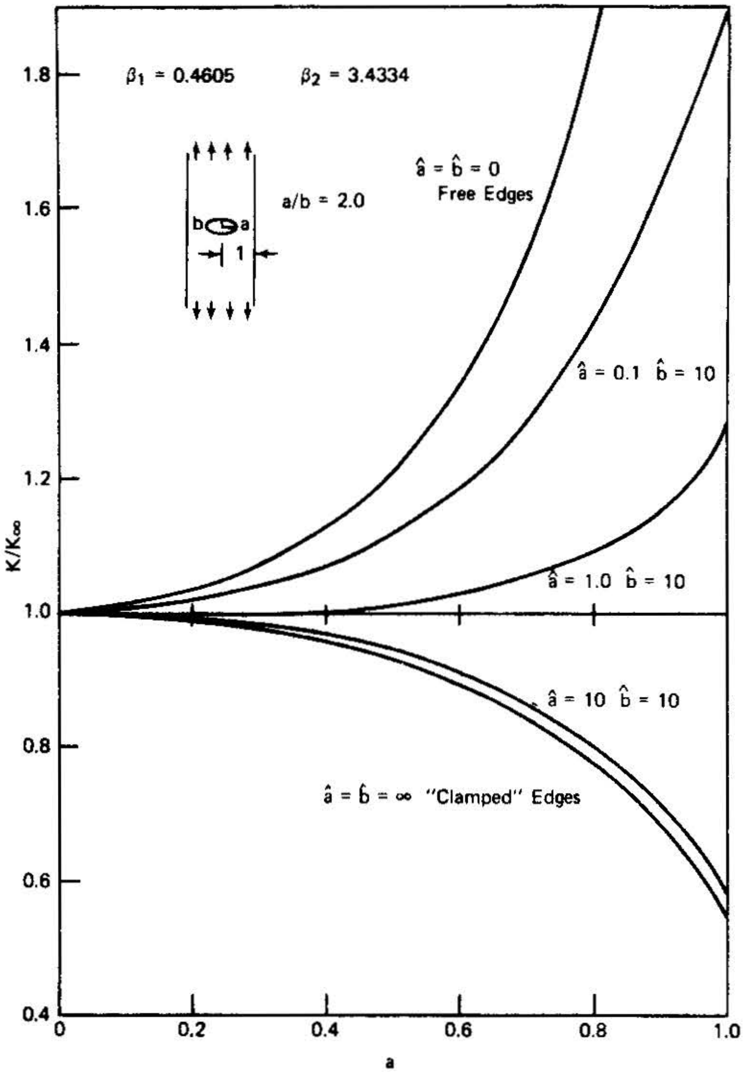

Figure 3b. Variation of peak stress with hole size: elliptical case.

points A or B, and K_∞ as the infinite domain value from Eqns. (5) or (6) the plots of Figs. 3a and 3b show K/K_∞ as a function of hole size. For the elliptical case the ratio of major to minor axes is taken as 2.0.

From the computer runs it was found that for a given value of $\hat{a}$, the stress values did not vary much with $\hat{b}$. Hence the bending effect may be taken as less pronounced than the shear effect. This agrees with Isida's findings for the isotropic case [3]. In Figs. 3a and 3b for the intermediate curves $\hat{b}$ is taken conveniently as 10. An examination of Figs. 3a and 3b reveals that with any increase in $\hat{a}$, i.e. relative area of stiffener the peak stress ratio decreases. This also has been found to be true in the isotropic cases of a crack studied by Isida [3].

Finally, we have in Fig. 4, a comparison between isotropic and orthotropic behaviours for the two limiting stiffener support cases. Here a relatively flat ellipse $a/b = 10$ (approaching the case of a crack) was chosen for the geometry. The isotropic case was generated by taking $\beta_1 = \beta_2 = 1$ in the computations. This curve agreed exceedingly well with Isida's results for a crack [3].

It is to be remarked that the results of Fig. 4 merely emphasize the fact that Eqn. (5) (or (6)) is highly material dependent. Each of B_{2n} depends on β_1, β_2 apart from other geometrical parameters Thus for a variety of orthotropic parameters it is possible to generate a family of

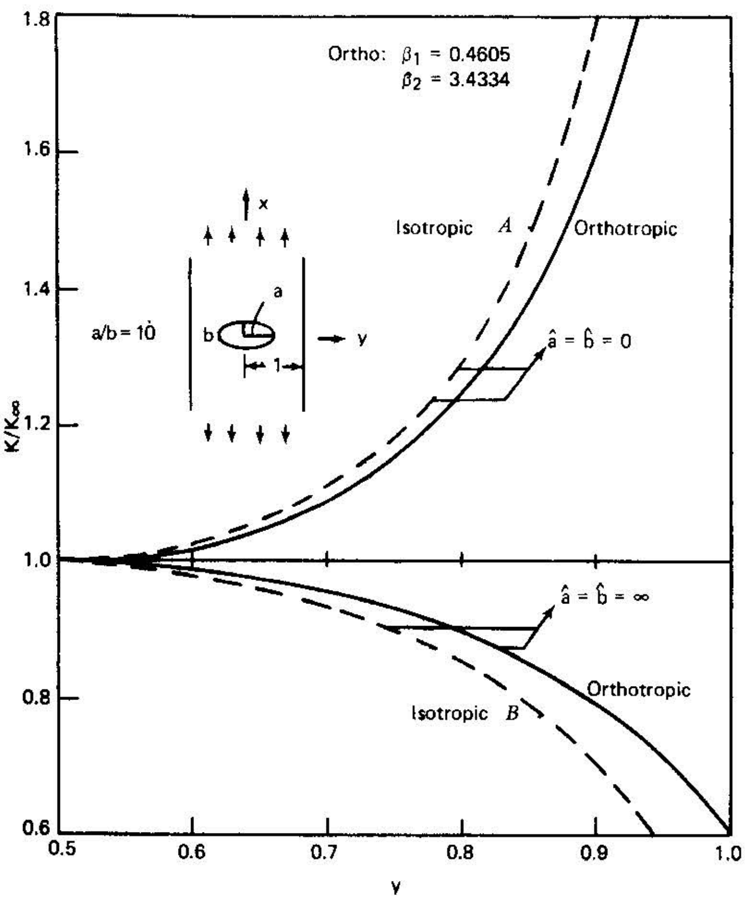

Figure 4. Comparison of isotropic and orthotropic behaviors for a flat ellipse.

curves corresponding to the (single) isotropic curve A or B in Fig. 4. Hence it is entirely possible to have a relatively more efficient structure for a given hole and stiffening geometry by suitable choice of orthotropic parameters. This brings to light the possibility that with the use of advanced fibrous composites relatively efficient structures can be built which have the potential to inhibit crack growth by virtue of material property as much as by added stiffening supports.

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RÉSUMÉ
L'article traite de l'analyse des contraintes dans des panneaux orthotropes comportant des raidisseurs d'extrémités et un trou dont la section est circulaire ou elliptique. Les profils des contraintes sont déterminés, pour chaque géométrie de trou, en fonction de la géométrie des raidisseurs. Les variations des contraintes sont également calculées en fonction de la dimension du trou, et ce pour différentes géométries de raidisseurs.

ZUSAMMENFASSUNG
Der Bericht behandelt die Spannungsanalyse für orthotrope Platten mit Endversteifungen und Löchern in der Mitte, mit elliptischem oder kreisförmigem Querschnitt. Für gegebene Lochgeometrien erhält man Spannungsprofile als Funktionen der Versteifungsgeometrien. Spannungsänderungen werden auch als Funktion der Lochausmessungen für verschiedene Versteifungsgeometrien berechnet.

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